Mars Rover Pair Cooperatively Transporting a Long Payload

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Abstract— *The objective of the Robot Work Crew (RWC) project is to investigate key challenges in multi-robot coordination when performing tightly coupled coordination tasks such as transporting and handling of long objects on challenging planetary terrain. In this paper, we focus on tightly coupled coordination of two Mars rovers transporting a long payload. We have developed practical decentralized compliancy control and coordinated comply control algorithms that effectively address compliant control for compliantly coupled multiple mobile robots. Experiments at the Jet Propulsion Lab in Pasadena, CA of two Mars rovers carry an extended payload over uneven, natural terrain are used to validate and illustrate the approach.*

Index Terms-*Planetary Rovers, Tight coordination, Decentralized Compliancy control, Multiple mobile robots.*

I. INTRODUCTION

Robotic outposts are relatively new NASA mission concepts that aim to establish permanent robotic presence on extra-terrestrial surfaces. These systems use multiples surface robots to conduct extensive science operations and pave the way for eventual human presence (human precursors) by deploying and assembling the infrastructure necessary for subsequent human missions. The Robot Work Crew (RWC) project at JPL is investigating challenges in multi-robot coordination when performing tightly coupled coordination tasks such as transporting and handling of long objects on challenging planetary terrain. This effort is also addressing cooperation and coordination schemes for both homogeneous and heterogeneous groups of mobile robots. Emphasis is on tasks that single robots cannot perform. RWC uses CAMPOUT [1] (Control Architecture for Multi-robot Planetary Outposts), a decentralized scheme with minimal explicit communication between platforms. CAMPOUT primarily uses implicit communication through the common load or object being handled or transported. Explicit communication is used only when necessary because of limited power budgets available in planetary exploration scenarios.

Recently, researchers have investigated transportation of large extended objects using autonomous distributed co-operating or coordinated multiple robots. The emphasis underlying these works have been on robust decentralized control schemes with limited state information exchange between robots. In most configurations, each robot is compliantly linked to a gripper or compliantly coupled to a common payload. Decentralized control schemes take advantage of locally sensed forces and moments exerted by the robots on the load to derive a control law to modify or generate new trajectories. In effect, the decentralized control schemes are compliant coordination schemes. Multiple mobile robot compliant control is very different from single mobile robot compliance control because the compliance frame is implicitly time varying, and the environment is not static due to continuous contact motion.

Several researchers have proposed decentralized control schemes for transportation of large objects using multi-mobile robots. Vinay et al. [2] presented simulation results of two mobile robots transporting a long object. A state space model for two wheeled mobile robots compliantly coupled to a common payload was developed using Lagrange techniques. State feedback control decoupled the system into 5 subsystems, simplifying and facilitating supervisory control design. Hisashi et al. [3] presented results of two cooperative mobile manipulators transporting a payload on uneven ground. Locking some of the joints of the manipulator and making the rest free achieved mechanical compliance. Khatib et al. [4], [5] proposed a general decentralized cooperative control algorithm for multiple mobile manipulators using an augmented object and a virtual linkage model. The experimental results presented demonstrate the potential effectiveness of the control scheme. Hara et al. [6], and Miyata et al. [7], presented a cooperative transportation control scheme for two quadruped robots transporting a payload. Several experimental results are presented, such as transporting the load over stairs. In general, many approaches reported for cooperative robot motion do not generalize; they do not consider activity within a natural (outdoor) terrain and/or fail to maintain an explicit continuous closed loop coordination of joint robot activities under physical constraints (rather, they use time-sequenced, iterative actions of the independent robots to partially address global task constraints).

The preliminary results presented here are based on a proposed robotic deployment of a modular solar photovoltaic (PV) tent array mission scenario as described in [8]. The study [8] demonstrated that a tent array of silicon PV cells could generate a nearly constant power profile. Such a PV tent array would be difficult to deploy using a solitary robot because the modules are 5 meters long and represent a considerable challenge for precision placement. Two cooperating robots can perform the task using the following steps [9]: *Pickup Phase:* Unload the container from the container storage unit (CSU), *Transport Phase:* Traverse to the deployment site, *Positioning Phase:* Position and open the container, and *Deployment Phase:* Deploy the PV tent. These steps were chosen to be consistent with the mass and power constraints for a mobile robot on the Martian surface. The results presented in this paper are based on the *Transport Phase* of the mission.

The sections of this paper that follow are organized as follows: Section II presents a brief description of the Sample Return Rover (SRR) and Sample Return Rover 2000 (SRR2K). Section III presents a detailed concept and formulation of the decentralized compliancy control strategy. Section IV presents the coordinated comply control behaviors. This is followed by a description of experimental studies in Section V. The paper closes with conclusions in Section VI.

II. MARS ROVERS DESCRIPTION AND CAPABILITIES

The two Mars rovers used in this research are the Sample Return Rover (SRR) and Sample Return Rover 2000 (SRR2K). SRR's chassis is a passive, instrumented rocker-type suspension with independent, active spur-gear differential articulated shoulder joints. The rover is equipped with a "micro-arm'' consisting of 3 degrees-of-freedom with an actuated gripping end-effector. SRR2K is identical to SRR except it has a fixed shoulder joint operating with a passive differential based rocker suspension. For the RWC experiments SRR and SRR2K were modified as follows. A fully instrumented 4 DOF (pitch, roll, yaw, and lateral translate) non-actuated gimbal was installed as shown in Figure 1. The gimbal incorporates a compliant gripper for "soft-grip'' of the payload and sits on top of a payload support beam to increase load carrying capacity of the vehicle. The range of motion of each degree of freedom in the rover frame (Figure 2) is as follows, passive yaw (+240° to –60°), spring-centered roll (±20°), spring-centered pitch (±20°), and spring-centered lateral translation (±2 cm) along the direction between the two robots. The gimbal mechanism is instrumented with a potentiometer for positional feedback of each degree of freedom. The entire gimbal mechanism is mounted to a 6-DOF load cell to resolve reaction forces. This load cell is then mounted to the cross-brace between the shoulders.

Figure 1 Gimbal Mechanism mounted on SRR.

III. DECENTRALIZED COMPLIANCY CONTROL BEHAVIOR

We use a decentralized control approach with no explicit communication except for synchronization signals between the rovers before initiating any activities. The emphasis of this paper is on the low-level decentralized comply control behaviors and the coordinated comply behaviors.

The low-level decentralized comply control behaviors are: *Formation Controller Behavior, Minimize Forces/Torques on Payload Behavior, and Center Payload in Longitudinal Slider Behavior.* The control inputs for each of these three controllers are (1) rover speed and (2) heading control (steering). The *Formation Controller Behavior* receives a desired formation angle command from the *Group Formation Behavior*. The desired formation angle is mapped into the corresponding gimbal yaw angles on each rover. The *Formation Controller Behavior* is then tasked with driving and steering the rover to achieve and maintain the desired gimbal yaw angle on each rover.

The *Minimize Forces/Torques on Payload Behavior* is tasked with minimizing the forces on the payload or compliant linkage on each rover. The forces on the payload can be high if the relative speed between the two rovers is greater than a set threshold. The magnitude of the 3-D force vector along the payload longitudinal axis is the input for this behavior. The predominant control output for *Minimize Forces/Torques on Payload Behavior* is rover speed, supplemented with steering corrections. The *Center Payload in Longitudinal Slider Behavior* is tasked with minimizing deviations of the payload from longitudinal slider center on each rover. A linear potentiometer is used to measure the gimbal slider position. The control output for *Center Payload in Longitudinal Slider Behavior* is rover speed and heading (steering) control.

The *Formation Controller Behavior*, *Minimize Forces/Torques on Payload Behavior,* and *Center Payload in Longitudinal Slider Behavior* controllers have conflicting goals. In actual operation, one may encounter a situation were *Center Payload in Longitudinal Slider Behavior* will request an increase in rover speed and *Formation Controller Behavior* would command a reduce speed.

To resolve this we developed a priority-based, weighted PD controller scheme for rover speed and heading trajectory modifications that satisfies *Formation Controller Behavior*, *Center Payload in Longitudinal Slider Behavior,* and *Center Payload in Longitudinal Slider Behavior* under steady state conditions. For each rover, we compute the formation error ϑ_{Lerror} (gimbal yaw angle error), the translation error T_{error} (deviation from gimbal slider center), and the force error F_{error} (magnitude of gimbal force vector along the payload longitudinal axis) as follows:

$$\vartheta_{Lerror} = \vartheta_{desired} - \vartheta_{actual} \qquad \textbf{\textit{Eq 1}}$$

where ϑ_{Lerror} is the gimbal yaw angle error, $\vartheta_{desired}$ is the desired gimbal yaw angle, and ϑ_{actual} is the actual gimbal yaw angle;

$$T_{error} = T_{desired} - T_{actual} \qquad \textbf{\textit{Eq 2}}$$

where T_{error} is the gimbal slider translation position error, $T_{desired}$ is the desired gimbal slider translation position, and T_{actual} is the actual gimbal slider translation position;

$$F_{error} = F_{desired} - F_{actual} \qquad \textbf{\textit{Eq 3}}$$

where F_{error} is the force error, $F_{desired}$ is the desired force error, and F_{actual} is the actual force reading.

First we define PD controllers to maintain formation angle (desired gimbal yaw angle), center payload and minimize payload forces as follows:

$$\vartheta_{out} = K_{p\vartheta}\vartheta_{error} + K_{d\vartheta}\frac{d}{dt}(\vartheta_{error}) \qquad \textbf{\textit{Eq 4}}$$

where ϑ_{out} is the output of the PD gimbal yaw angle controller, $K_{p\vartheta}$ is the proportion gain of the PD gimbal yaw angle controller, and $K_{d\vartheta}$ is the derivative gain of the PD gimbal yaw angle controller;

$$F_{out} = K_{pF}F_{error} + K_{dF}\frac{d}{dt}(F_{error}) \qquad \textbf{\textit{Eq 5}}$$

where F_{out} is the output of the PD force controller, K_{pF} is the proportional gain of the PD force controller, and K_{dF} is the derivative gain of PD force controller;

$$T_{out} = K_{pT}T_{error} + K_{dT}\frac{d}{dt}(T_{error}) \qquad \textbf{\textit{Eq 6}}$$

where T_{out} is the output of the PD gimbal slider translation position controller, K_{pT} is the proportional gain of the PD gimbal slider translation position controller, and K_{dT} is the derivative gain of the PD gimbal slider translation position controller.

The PD controllers defined above independently achieve their respective goals but when implemented simultaneously will result in conflicting speed and heading corrections. To resolve these conflicts, we combined the outputs of each of the PD controllers into a single function using a weighting scheme to compute the desired speed and heading corrections for each rover. The weighted functions are defined as follows:

<u>Lead Rover:</u>

$$\Delta Vel = -W_{\vartheta}\vartheta_{out} + W_F F_{out} - W_T T_{out} \qquad \textbf{\textit{Eq 7}}$$

such that

$$W_{\vartheta} + W_F + W_T = 1.0 \qquad \textbf{\textit{Eq 8}}$$

<u>Follow Rover:</u>

$$\Delta Vel = W_{\vartheta}\vartheta_{out} + W_F F_{out} - W_T T_{out} \qquad \textbf{\textit{Eq 9}}$$

such that

$$W_{\vartheta} + W_F + W_T = 1.0 \qquad \textbf{\textit{Eq 10}}$$

where ΔVel is the required speed correction factor, W_{ϑ} is the weight assigned to the PD gimbal angle controller output, W_F is the weight assigned to the PD force controller output, and W_T is the weight assigned to the PD gimbal translation position controller;

$$\Delta Hd = W_{H\vartheta}\vartheta_{out} + W_{HF}F_{out} + W_{HT}T_{out} \qquad \textbf{\textit{Eq 11}}$$

such that

$$W_{H\vartheta} + W_{HF} + W_{HT} = 1.0 \qquad \textbf{\textit{Eq 12}}$$

where ΔHd is the required rover heading correction factor, $W_{H\vartheta}$ is the weight assigned to the PD gimbal angle controller output, W_{HF} is the weight assigned to the PD force controller output, and W_{HT} is the weight assigned to the PD gimbal translation position controller. The combined control laws for these controllers are best characterized by considering the following cases:

<u>Case 1: Rovers in a row transport formation (zero formation angle).</u>
Ideally, in a row formation the gimbal angles of both rovers are zero degrees (i.e. the rovers are aligned and the longitudinal axis of the beam is perpendicular to their heading figure 3a). During a traverse, both rovers deviate from their path due to differences in velocities, ground slippage, terrain effects, etc. These result in two undesirable consequences: (1) the payload will not be centered in the gimbals, and (2) the forces on the payload will exceed the desired threshold.

The heading correction equation (11) was very difficult to implement in the row formation due to the slow response of the steering actuators. Therefore a force threshold was set, and if the threshold is exceeded on either rover, both rovers stopped, synchronized, and took turns to center the payload. The speed corrections proved to be very effective. It was used in a traverse of over 30 meters. In the row formation the following weights were used:

$$W_{\vartheta} = 0.6, W_{T} = 0.3, W_{F} = 0.1$$

$$W_{H\vartheta} = 0.0, W_{HF} = 0.0, W_{HT} = 0.0$$

<u>Case 2: Rovers in a column transport formation figure 3g, lead-follower scheme (formation angle greater 10° but less or equal to 85°).</u>
Similar to the row formation during traverse, both rovers will deviate from their path due to difference in speeds, ground slippage, terrain effects, and other disturbances. These will result in the payload not being centered in the gimbals and forces on the payload exceeding the desired threshold. Here also we use the same priority based weighted PD controller scheme for rover speed and heading trajectories modifications that satisfies *Formation Controller Behavior*, *Center Payload in Longitudinal Slider Behavior,* and *Center Payload in Longitudinal Slider Behavior* forces under steady state conditions. However the weights are different from the row formation scheme. In the column formation the following weights were used:

$$W_{\vartheta} = 0.05, W_{T} = 0.90, W_{F} = 0.05$$

$$W_{H\vartheta} = 0.85, W_{HF} = 0.1, W_{HT} = 0.05$$

Figure 2 SRR and SRR2K transporting long payload in column (diagonal) formation.

IV. GROUP COMPLIANCE CONTROL BEHAVIORS

The group behaviors are organized in a hierarchical framework with the group compliance behaviors at the lowest level of the hierarchy. The low-level decentralized compliance control behaviors rely on the group compliance behaviors for their inputs. The group compliance behaviors are derived by considering the tightly coupled multi-robot system depicted in Figure 2 as a single vehicle system. The compliance coordination behaviors employ implicit communication through the shared payload and limited explicit communication for synchronization of activities. There are three main group compliance behaviors; *Group Center Load*, *Group Formation*, and *Group Transport*. These group compliance behaviors are explained in more detail as follows:

1) *Group Formation*

The group formation behavior changes the formation of the rovers between any arbitrary start and end formation. Figure 3 illustrates the sequence of motions that occur to change formation. In Figure 3a we assume a scenario where the rovers are in row formation in group transport behavior when a change formation command is received. Each rover has a specific role, and their actions occur simultaneously. The role of the lead rover is to drive a pre-determined trajectory along an arc to change the formation. At the same time, the wheels of the follow rover are continuously aligned with the load and it simultaneously drives forward or backward to ensure that the load is centered in its gimbal and load forces are minimized. The following steps occur in sequence to change the formation: Step 1: The follow rover aligns its wheels with the load and the lead rover waits (as shown on Figure 3b). Step 2: The lead rover turns its wheels to drive along the pre-determined arc trajectory (Figure 3c). Step 3: As the lead rover drives along an arc, the follow (pivot) rover continuously aligns its wheels with the load and drives forward or backward based on sensory inputs from its gimbal to compensate for the lead rover's deviations from the arc (that inevitably occur due to ground slippage, terrain effects, etc.). (Figure 3d). Step 4: When the lead rover has traversed the arc, the lead rover steers its wheels into a turn-in-place (point turn) configuration. At the same time, the follow rover straightens its wheels back to its original wheel configuration. (Figure 3e). Step 5: The lead rover turns in place until the load is at the commanded formation angle (Figure 3f).

2) Center load

The *Center Load* behavior is activated when the force in the gimbal on either of the rovers exceeds a specified threshold. Figure 3 illustrates the sequence of motions that occur to center the load on both rovers and reset the force. In Figure 3h we depict a scenario where the rovers are in column formation in group transport behavior when the center behavior is triggered. The corrective procedure is for each rover to center the load with respect to the center of its gimbal. The arrows on Figure 3h illustrate the misalignment. In the corrective procedure, the lead rover performs its correction while the follow rover waits. When the lead rover has completed its correction, the rovers reverse roles and the follow rover performs its correction. The following steps occur in sequence during the center load behavior: Step 1: Synchronization occurs between the rovers to indicate triggering of the center load behavior. Both rovers then halt and enter the group center load behavior. (Figure 3h illustrates the rovers in this configuration). Step 2: The lead rover turns its wheels to align them with the load (as illustrated on Figure 3i). The distance to drive to correct the misalignment is determined by reading the displacement from the gimbal translate sensor (the sign indicates the direction to drive in). Step 3: The lead rover then drives the appropriate distance to correct for the misalignment, upon completion of the correction; the lead rover straightens its wheels. Step 4: The rovers reverse roles. The follow rover also performs Steps 2 and 3.

3) Group Transport

The group transport behavior coordinates the motion of the two rovers in a desired formation. During a traverse, both rovers continuously modify their heading (i.e. steering trajectories) and velocity trajectory profiles to ensure that the formation is maintained, the load is centered in their gimbals and gimbal forces do not exceed a specified threshold. The following steps occur in sequence during group transport: Step 1: The rovers get into the commanded formation using the Group Formation behavior. Step 2: The rovers synchronize to initiate driving. Step 3: During driving, the state information (force, torque, and translation) from the gimbal on each rover is used to continuously modify velocity and heading of the rovers. Step 4: During transport, excessive force in the load on either rover may trigger a Center load behavior. The rovers perform the Center load behavior. Upon completion of the Center load behavior, the Group transport behavior resumes (Steps 1, 2 and 3) until the transport distance is completed.

V. Experimental Results

The developments described have been demonstrated in a representative scenario of the transport phase of the PV Tent deployment. In the demonstration, the coupled rovers are initialized in the configuration where they are both holding the container as they would immediately after picking it up from the container storage area. Specifically, the transport phase consisted of backing up 5 meters from the storage area, using the Group Transport Behavior, rotating 180 degrees using the Group Formation Behavior, then driving 40-to-50 meters to the desired deployment area again using the Group Transport behavior. The Center Load Behavior is initiated at any time during the execution of the transport phase. This will occur when the gimbal sensors indicate the need to center the load because the longitudinal force in the container exceeds the set threshold. These autonomous operations were successfully demonstrated at a site in the Arroyo Seco, a dry riverbed that has a relatively open terrain with a slope of less than 9 degrees.

VI. Conclusions

We have presented a decentralized and group coordinated compliancy control behaviors applied to a Mars rover pair transporting a long payload over uneven, natural terrain. This is one of the first reported efforts that have been successfully completed in such an environment. During the next fiscal year we will concentrate on the development of the grasp and manipulate behaviors that are necessary for the first, third and fourth steps in the PV tent deployment mission scenario.

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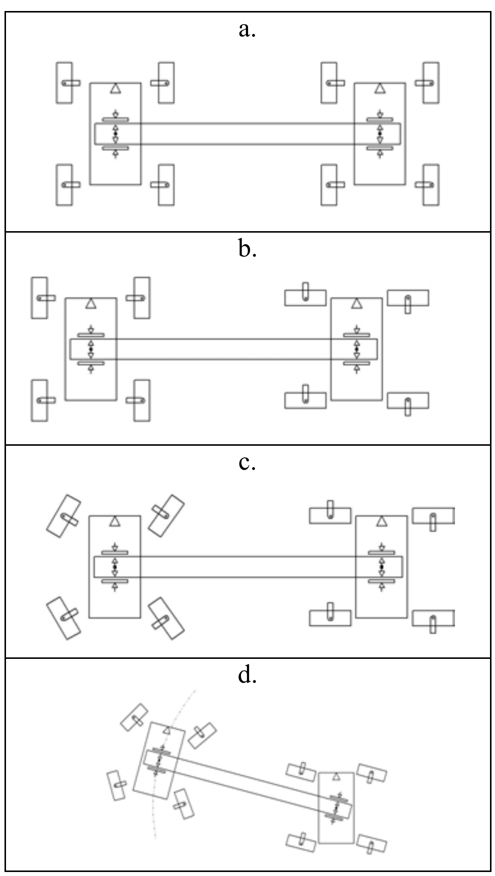

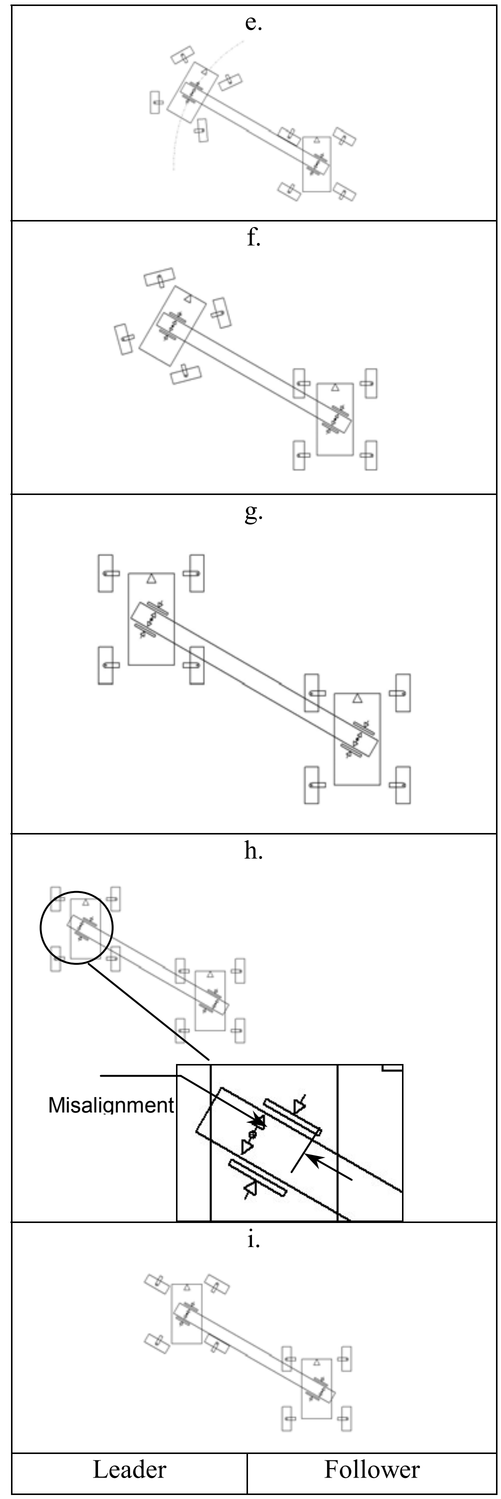

Figure 3 Distinct phases of the group formation and group center load behavior**.**